
# A USER-FRIENDLY TOOL FOR EVALUATING THE THERMAL RESPONSE OF HIGH POWER BATTERY PACKAGING ALTERNATIVES

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# Overview

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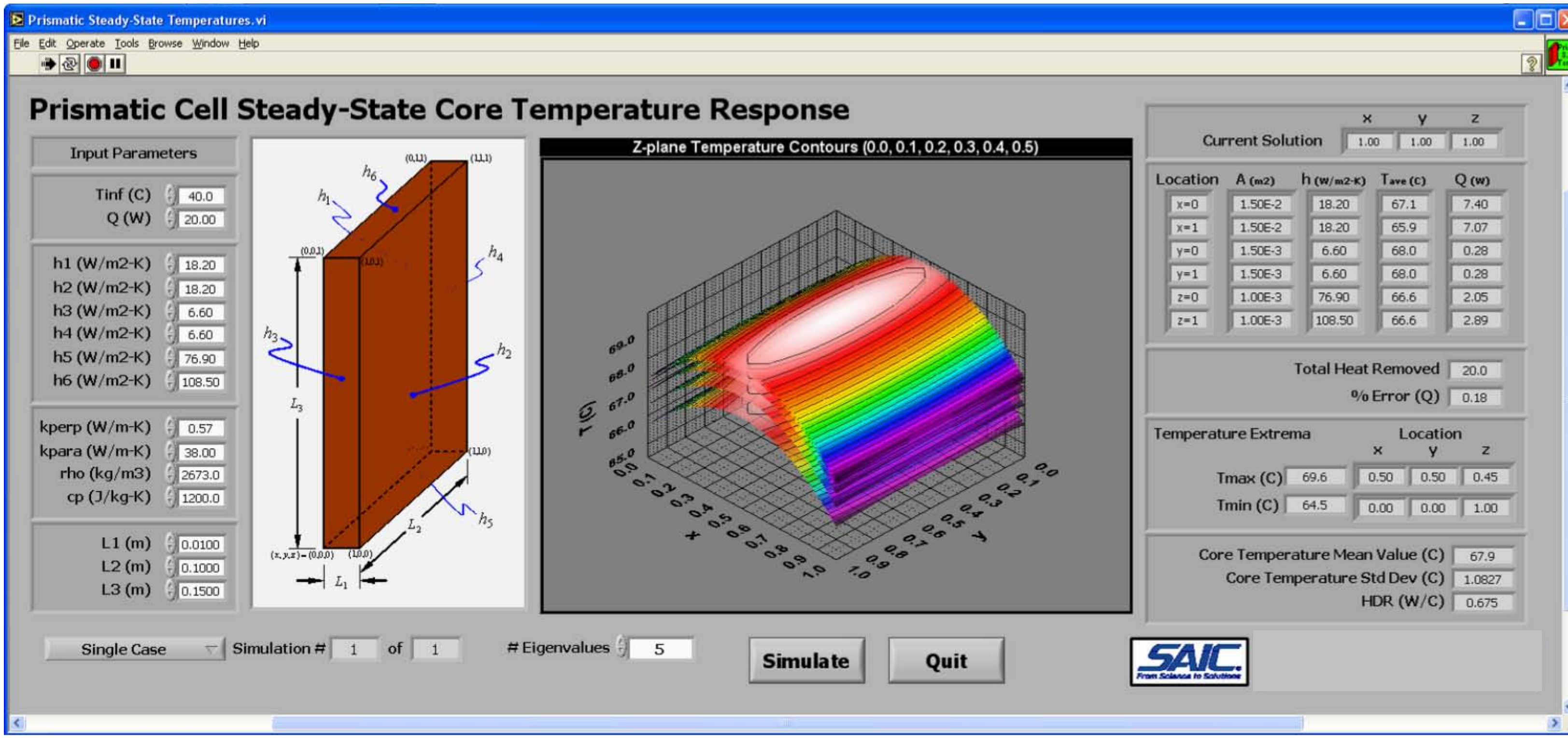
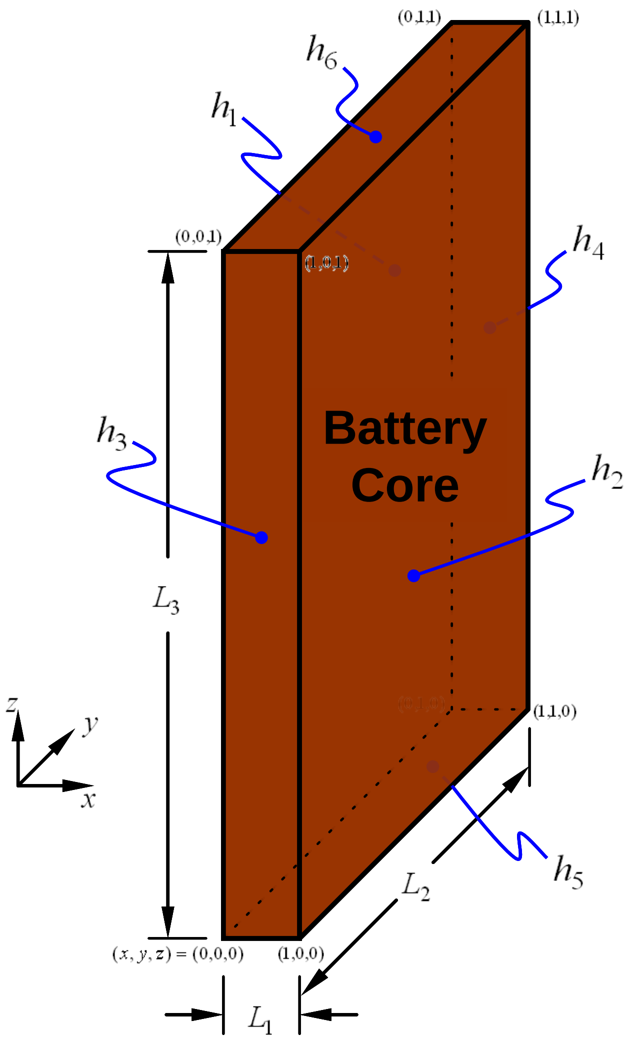
- Latest generation of high power battery cells are often comprised of multiple alternating layers of anode, cathode, separator and electrolyte
- Macroscopically, battery cores represent an orthotropic material subject to a time variant heat source
- Safety and performance considerations place a premium on packaging design and installation thermal maintenance
- SAIC has developed a numerical solver tool to evaluate thermal performance of packaging alternatives that will:
  - Run rapidly (avoiding costly finite element simulations)
  - Evaluate multiple geometries (prismatic, cylindrical, annular cell arrangements)
  - Provide flexibility for multiple configurations (air or liquid cooling)
  - Support steady-state and transient solutions
  - Quantify predictive uncertainty
- Allows for internal cell temperature prediction where instrumentation is difficult, at best

# Cartesian Steady-State Solver for Prismatic Battery Cells




- Solver predicts temperature response within the battery core based upon user supplied input of geometry, cell properties, boundary conditions and heating rate
- User can select mesh refinement and degree of simulation precision

# Cartesian Solver for Prismatic Battery Cells




- Solves for temperature profiles as a function of coolant temperature, heating rate, effective boundary conditions and cell properties

$$\rho c_p \frac{\partial T}{\partial t} = k_\perp \frac{\partial^2 T}{\partial x^2} + k_\parallel \frac{\partial^2 T}{\partial y^2} + k_\parallel \frac{\partial^2 T}{\partial z^2} + \dot{Q}_v(t)$$

- The solution solves for temperature response with effective convective boundary conditions along all six faces of the cell core utilizing boundary conditions of the third kind

$$k_\perp \frac{\partial T}{\partial x}\bigg|_{x=0} = h_1(T_1 - T_\infty) \quad , \quad -k_\perp \frac{\partial T}{\partial x}\bigg|_{x=L_1} = h_2(T_2 - T_\infty)$$

$$k_\parallel \frac{\partial T}{\partial y}\bigg|_{y=0} = h_3(T_3 - T_\infty) \quad , \quad -k_\parallel \frac{\partial T}{\partial y}\bigg|_{y=L_2} = h_4(T_4 - T_\infty)$$

$$k_\parallel \frac{\partial T}{\partial z}\bigg|_{z=0} = h_5(T_5 - T_\infty) \quad , \quad -k_\parallel \frac{\partial T}{\partial z}\bigg|_{z=L_3} = h_6(T_6 - T_\infty)$$

- Similar forms exist for cylindrical cells

# Cartesian Steady-State Solver for Prismatic Battery Cells

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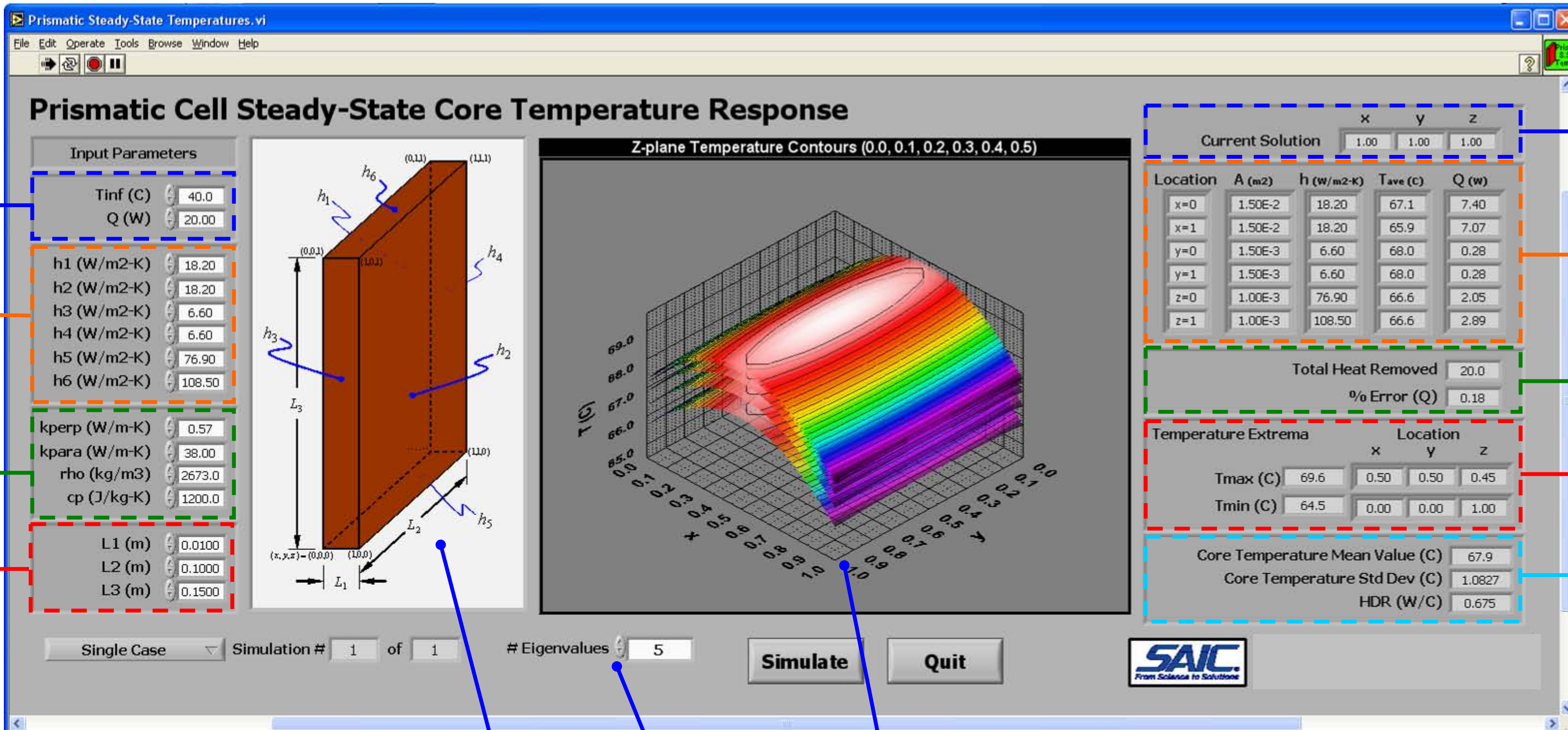


Battery Dimensions

Battery Core Properties

Effective Heat Transfer Coefficients

Problem Specifications

Geometry Depiction

Number of Eigenvalues (per coordinate direction)

Dimensionless Temperature Profiles
$T=f(x/L_1, y/L_2)$
at $z/L_3=(0.0, 0.1, 0.2, 0.3, 0.4, 0.5)$

Core Temperature Statistics

Temperature Extrema and Locations

Energy Balance Solution Check

Core Face Values

Solution Location Monitor

# Results of Several Baseline Verification Simulations

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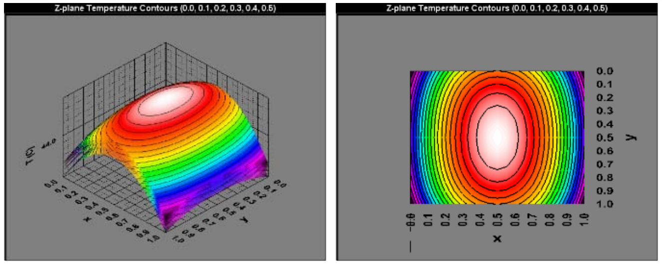
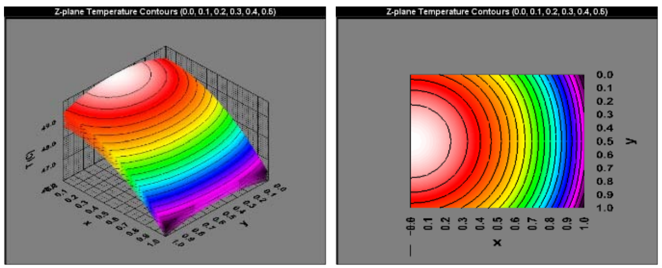
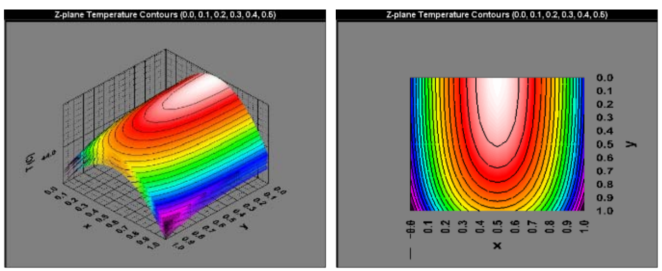


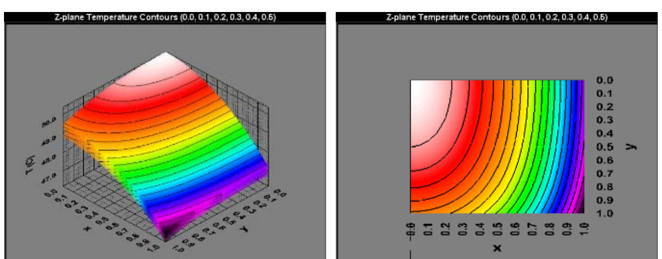

- Uniform heat transfer coefficients
  - Note increased gradients in x-direction due to orthotropic properties




- Adiabatic conditions along x=0 face




- Adiabatic conditions along y=0 face




- Adiabatic conditions along x=0 & y=0 face



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# Solver Example – Prismatic Cells Between Liquid Coldplates

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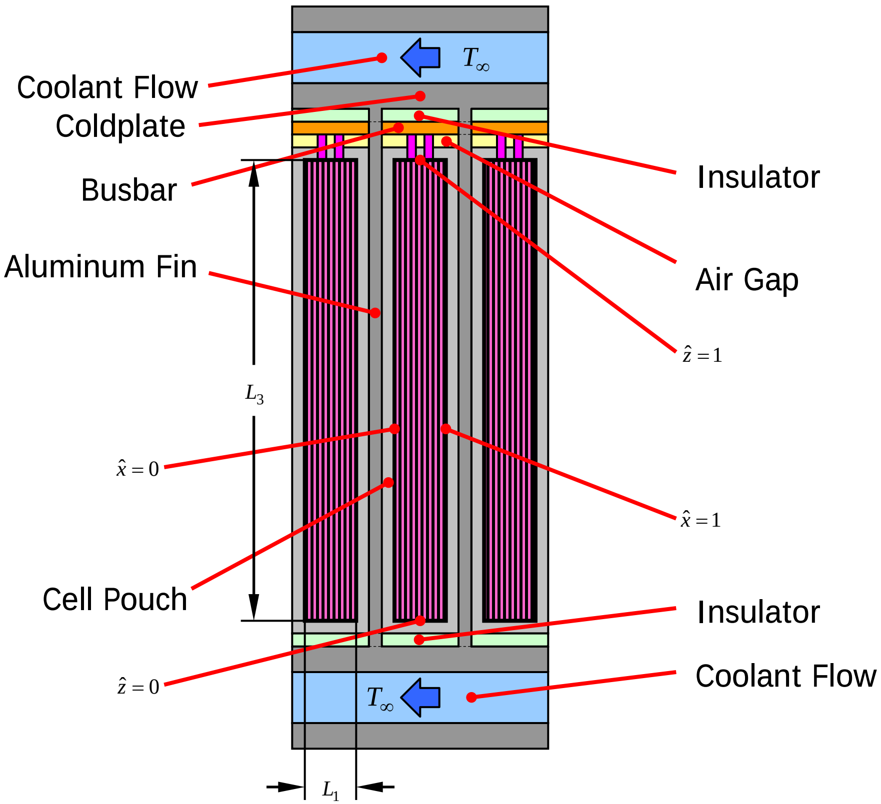
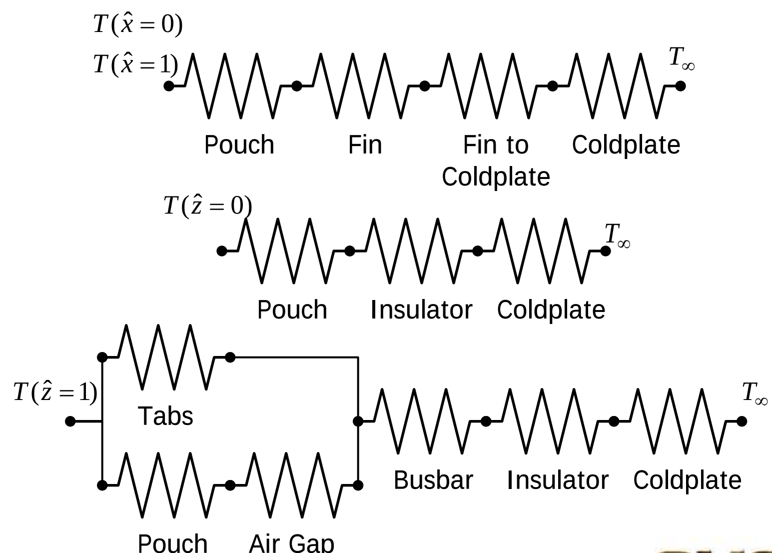
- A generic prismatic cell (15×10×1 cm) with sandwiched between cold plates – aluminum interstitial plates act as cooling fins for cell lateral surfaces
- Effective heat transfer coefficients estimated through analogous thermal circuits
- Similar approach used for y-direction effective heat transfer coefficients

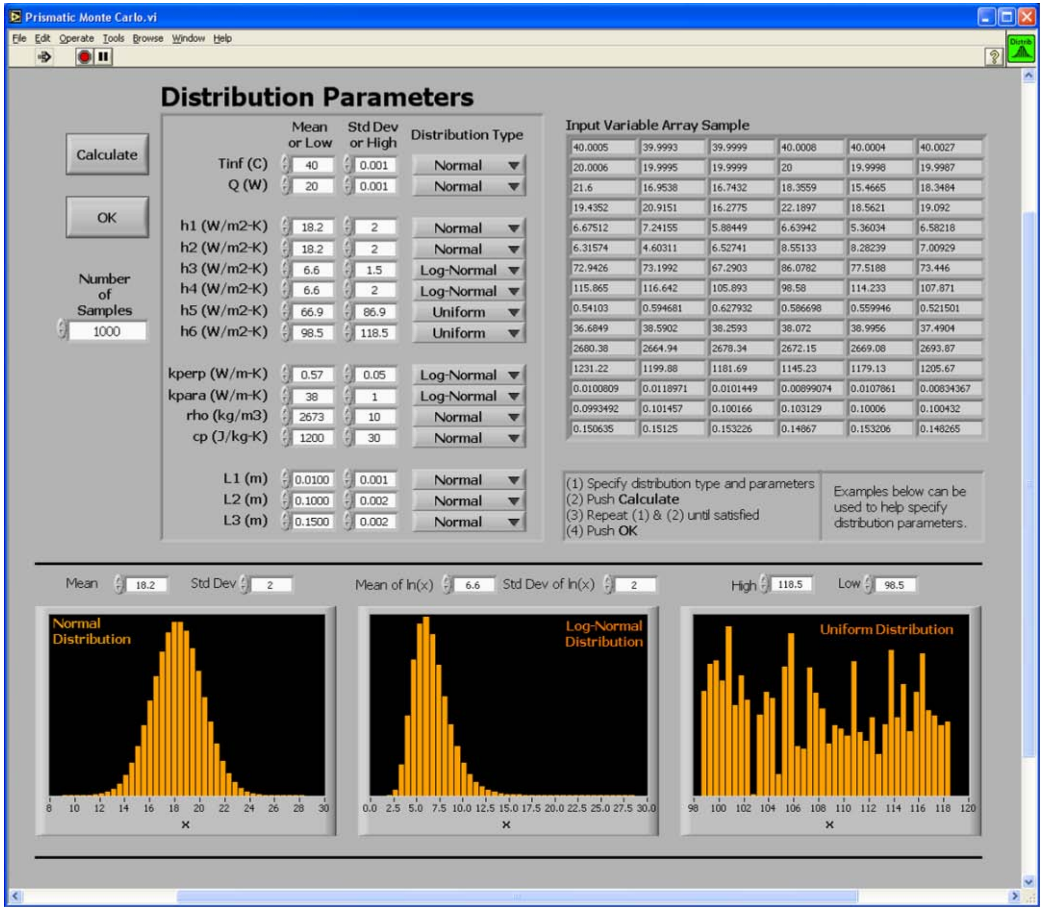



$$\frac{1}{h_{eff}\,A} = \sum_n \frac{1}{h_n A_n} + \sum_m \frac{\Delta x}{k_m A_m}$$



# Monte Carlo Simulation Tool

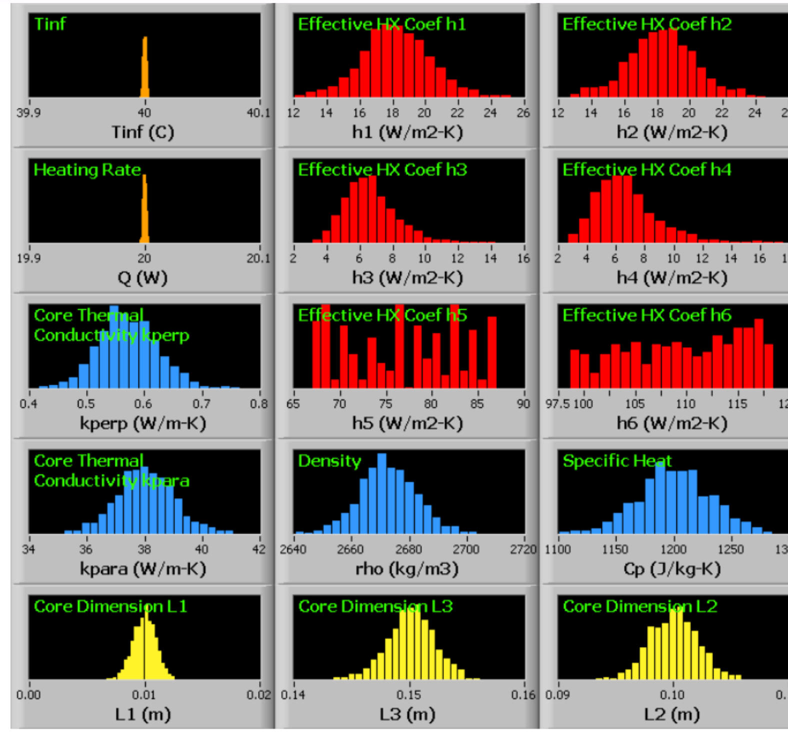
- To quantify uncertainty, a Monte Carlo simulation tool has been developed
- User selects distribution type and parameters
- Currently supports:
  - Gaussian distributions
  - Log-normal distributions
  - Uniform distributions
- User tool has distribution samples to aid user identification
- User selects number of Monte Carlo samples to simulate



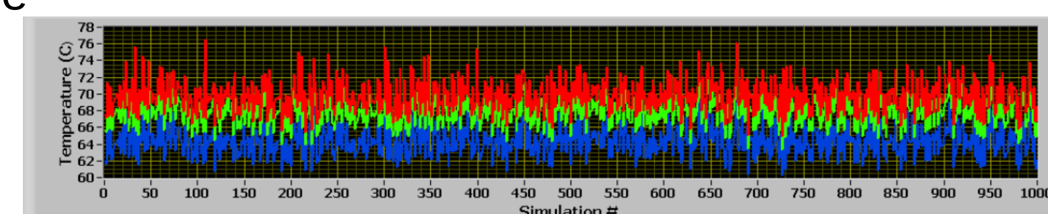

**Monte Carlo Simulation Distribution Parameters Input Screen**

# Monte Carlo Simulation Results

- Monte Carlo simulation runs multiple simulations using random sampling from defined variable distributions
- Simulations run rapidly – 1000 samples runs in a matter of minutes on a laptop
- Allows for rapid evaluation of uncertainty
  - Material properties
  - Heating rate
  - Boundary conditions
- Solver plots battery cell maximum, minimum and average temperature




**Input Property Distributions**




**Monte Carlo Simulation Results**

# Monte Carlo Simulation Results

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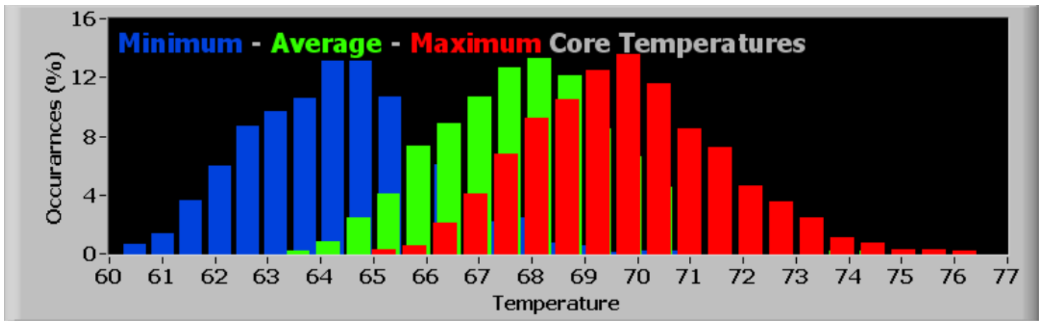
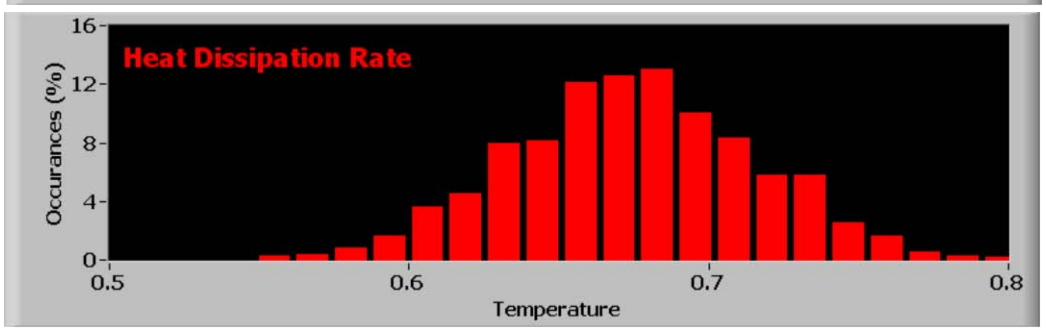
- The solver post-processes the Monte Carlo simulation results to give:
  - Distributions for the minimum, average and maximum core temperatures
  - Heat Dissipation Rate (HDR) distribution
  - Parameters of those distributions (mean and standard deviation)




| | |
|---|---|
| Tmax mean | 69.77 |
| Tmax std dev | 1.83 |
| Tave mean | 68.03 |
| Tave std dev | 1.80 |
| Tmin mean | 64.39 |
| Tmin std dev | 1.72 |
| HDR mean | 0.67 |
| HDR std dev | 0.04 |

**Distribution Parameters**

- Heat Dissipation Rate (HDR) is a measure of the package cooling effectiveness and is defined as:

$$HDR = \frac{\dot{Q}}{T_{Max} - T_{Coolant}}$$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# Utilizing Results

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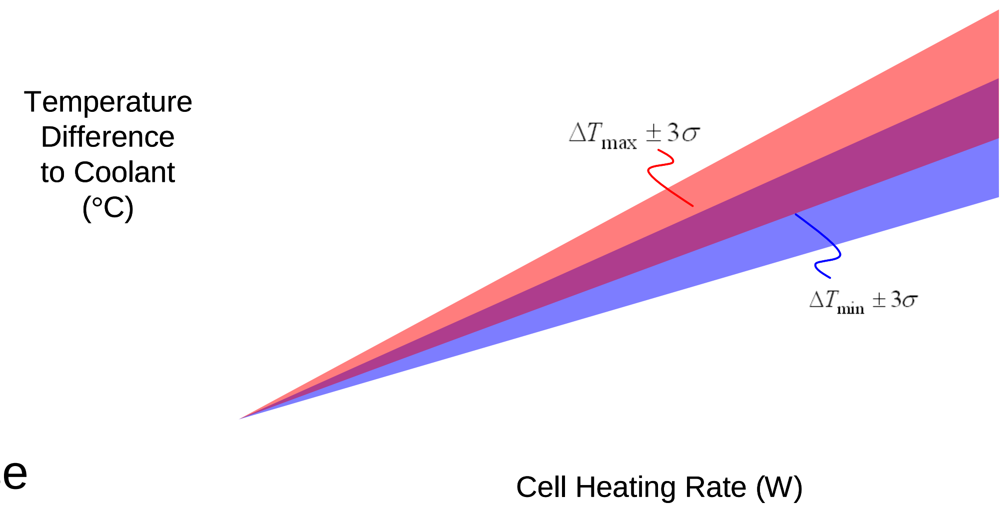
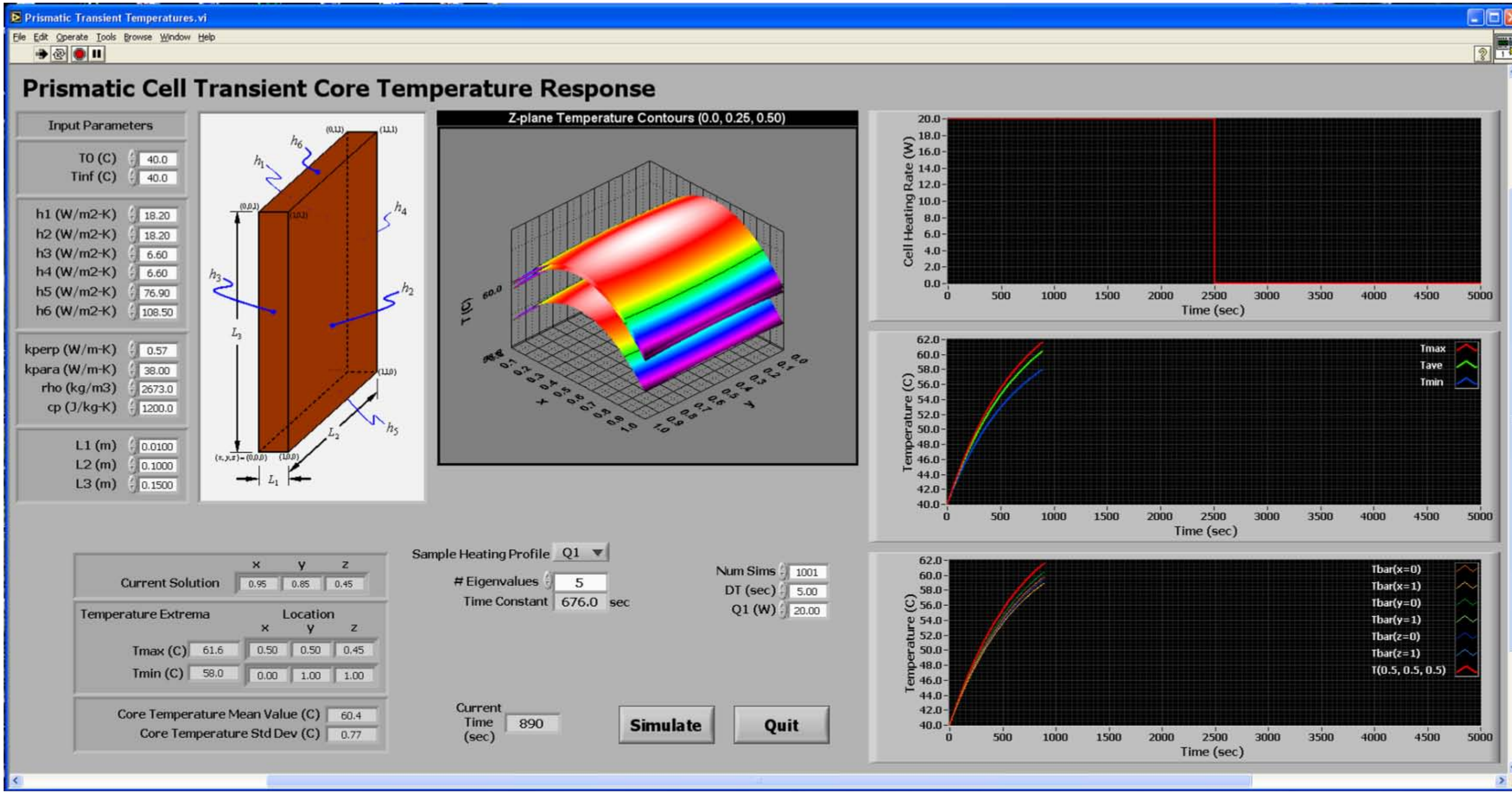
- Heat Dissipation Rate (HDR) can be used to quantify the expected temperature difference from the cell to the coolant as a function of heating rate
- HDR leads to predictive of maximum and minimum core temperatures as a function of heating rate
with uncertainty bounds (±3σ)

$$HDR = \frac{\dot{Q}}{T_{Max} - T_{Coolant}}$$




- This illustrates best- and worst-case cooling scenarios for this particular packaging design
- For example, at a 30°C coolant temperature and a 15W cell heat load
  - $\Delta T_{max}$ (Cell max temperature – Coolant Temperature) = 27 C
  - Worst-case maximum core temperature is predicted to be $48 < T_{max} < 57$°C.

# Cartesian Transient Solver for Prismatic Battery Cells




- Allows for transient simulation of time-variant heat loads
- Heat loads can be user defined or uploaded from tab-delimited files

# Transient Results
# Step Discharge Case

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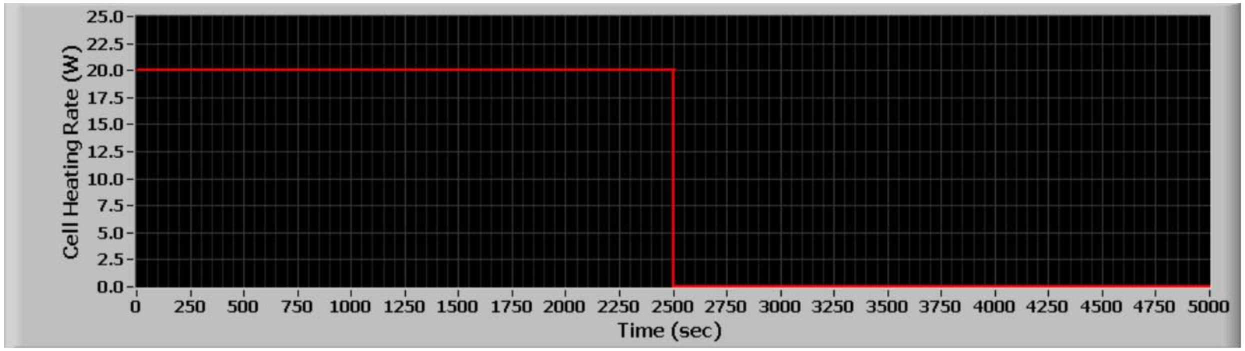
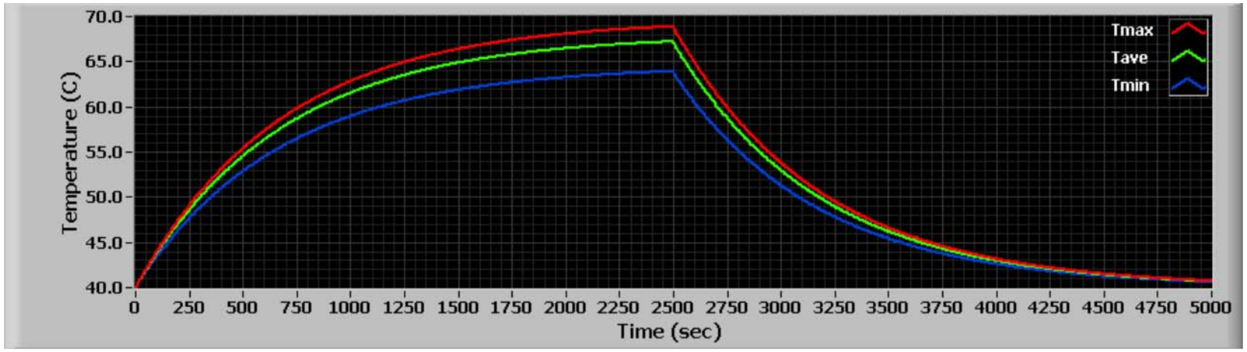
- Results of a step change in heating from initial conditions




**Cell Heating Rate**

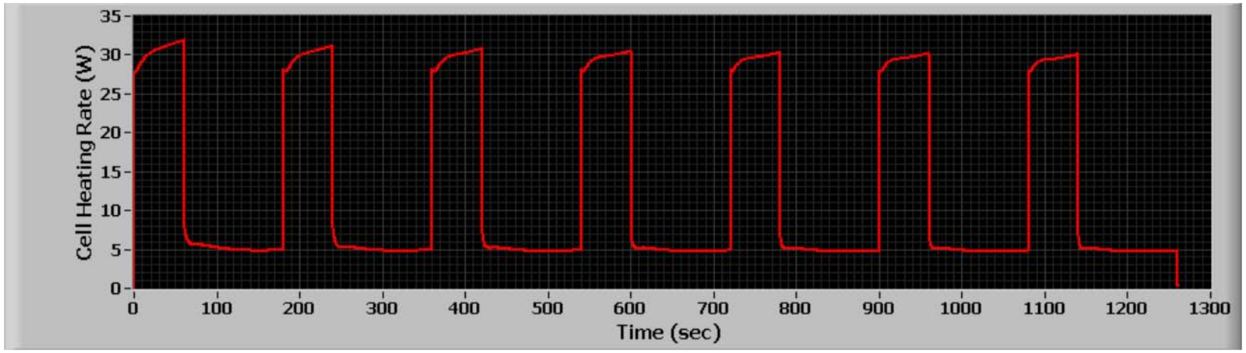



**Battery Core Temperature Response**

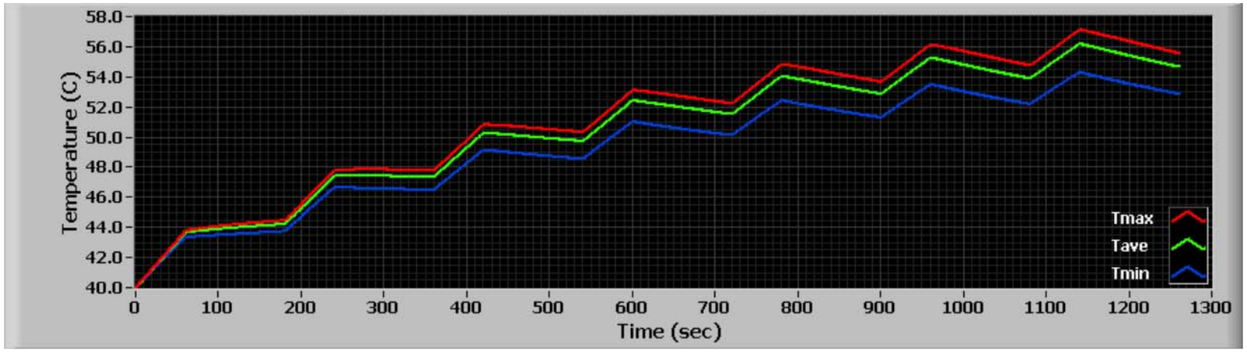
- Identifies battery packaging concept time constant, worst case loading expectations and recovery time

# Transient Results
# Load Leveling Case

- Load-leveling presents a challenging thermal demand
- This case represents the temperature response to repetitive cycles of 60 sec discharge (100A) and 120 sec charge (50A)



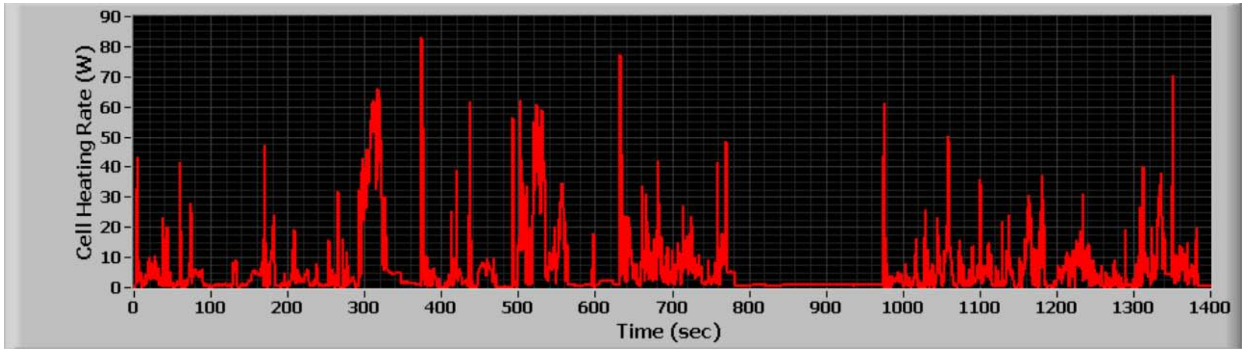

**Cell Heating Rate**



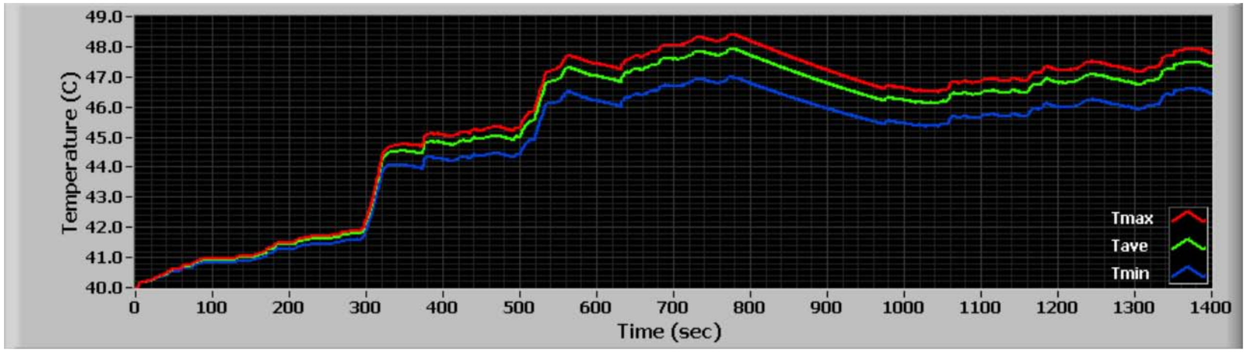

**Battery Core Temperature Response**

# Transient Results
# Driving Scenario Case

- Realistic driving scenarios imposed on a battery used for mobility assist
- Profiles typically show extensive non-uniformity




**Cell Heating Rate**




**Battery Core Temperature Response**

# Wrap Up

- Thermal solver predicts internal battery core temperature response
- Steady-state and transient applications
- Different geometries supported – prismatic, cylindrical, annular
- Monte Carlo simulator included to quantify uncertainty
- Several future developments are envisioned:
  - Link to battery performance tool (electrical model)
  - User tools to support boundary condition estimation
  - Inclusion of transient coolant temperatures
  - Temperature dependent property effects
  - External package thermal inertia effects
- Questions / Comments / Feedback